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Open-source based geo-platform to support management of wetlands and biodiversity in Quebec

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ABSTRACT

Wetlands are one of the most productive environments in the world. Despite their importance for water and carbon cycle regulation, wildlife survival and economic value, human activities along with severe climate changes have led to critical loss and degradation of these ecosystems. In Canada, where these lands still occupy a notable percentage of the territory (~14%), efficient strategies and public awareness measures to protect them are required. The Open Government program fosters accessibility to a large amount of data for developing approaches and applications that contribute to this purpose. Web cartographic implementations represent a potential tool for integration and diffusion of diversified information that can support the protection of natural habitats.

In this paper, we present an open-source geo-platform that supports multi-scale management of wetlands and biodiversity in Quebec. This friendly and dynamic prototype allows integration of multisource data, providing, as well, the possibility of geovisualization and correlation analysis of possible stressors impacting these ecosystems. This system proposes useful and easy-to-use functionalities that can facilitate identification of possible habitats in danger. The prototype proposed is flexible and can be adapted to assist other biodiversity studies as well as the practical needs of responsible groups such as planners, conservationists and landscape managers.

1. Introduction

Actual and future trends of human population (UNDESA, 2015), unsustainable urban sprawl and land use practices (UNDESA, 2014) suggest that further loss of wetlands, perturbation of their ecological functions and disappearance of local biodiversity may persist. In Canada, where wetlands cover 14% of the territory and represent 25% of the world's reserves, a notable loss of these unique ecosystems have been recorded (Environment Canada, 2009). Particularly, in Canadian prairies, intensive agriculture practices have rapidly deteriorated and reduced the number of wetlands (Bartzen et al., 2010). In southern Canada, expansion of built-up areas (urban and/or rural) has affected these natural habitats, especially where agglomerations and industrial centres are developed (Canadian Wildlife Service and Environment Canada, 2014). In Quebec, where about 10% of the territory is covered by wetlands (Gouvernement du Québec, 2016), there has been a significant progress in environmental protection and conservation actions (Environment Canada, 2009; Joly et al., 2008). Nevertheless, deterioration of wetlands is still a critical issue.

In the recent years, the Government of Canada has fostered accessibility to a large amount of high-value data useful for developing essential applications that can contribute to basic conservation of wetlands and biodiversity (Government of Canada, 2016a). This large database has rapidly increased due to the advent of new technology that allows fast acquisition of data, at a relatively low cost, compared to traditional in-situ surveys. Satellite imagery, for example, has notably contributed to the mapping, inventory and monitoring of wetlands (e.g., Rebelo et al., 2009; Sun et al., 2016) and habitat change at a global scale (e.g., All and Nelson, 2008; Kim et al., 2014). On the other hand, Geographic Information systems (GIS) allow the integration and analysis of data that can be shared and visualized via Web GIS applications. The Canadian Ducks Unlimited Organization has developed various tools that fulfil these tasks (e.g., Canada Wetland Inventory Progress; Ducks Unlimited Canada, 2016a). Many programs concentrate on the production of interactive maps that provide valuable information on wetlands at local (e.g., Smith Creek Watershed; Ducks Unlimited Canada, 2016b) and regional scale (e.g., Ducks Unlimited Canada, 2014; Ducks Unlimited Canada, 2016c) as well as on related components (Ducks Unlimited Canada, 2008). Some of these implementations are based on commercial applications (e.g., Esri ARCIms) which flexibility for being extended or adapted to particular objectives may be restrained. However, according to the Open Government

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program guidelines (Government of Canada, 2016a), open source geoplatforms are desirable.

Although the existing platforms are very effective in wetland mapping none of them cover the entire province of Quebec. Moreover, to the authors' knowledge, no open-source-based interactive map that integrates wildlife and elements that allow a preliminary evaluation of possible threats to these ecosystems has been produced up to now in the province.

This work presents a preliminary Web GIS prototype for supporting preservation of wetlands and biodiversity in Quebec. This system facilitates combination, interaction and visualization of various datasets that help characterization of wetlands state. The system offers useful functionalities for rapid identification of fragmented habitats and evaluation and/or readjustment of possible zonation areas to protect wildlife. Additionally, data access at different spatial scale is possible thanks to a multiscale functionality.

The remainder of this paper is organized as follows. Section 2 briefly describes the main issues in wetland and biodiversity preservation in Quebec. In Section 3 the available datasets employed and their formats are presented, and the role of some key stressors in the ecosystems functioning of the province is addressed. Sections 4 and 5 characterize the web system architecture, database and components. Section 6 discusses some case examples of useful services the portal offers and future perspectives. Finally, conclusions are presented in Section 7.

2. Overview of the situation of wetlands in Quebec

Quebec, the second most populated province of Canada (NRCAN, 2016a; 8,263,600 people in 2015; André, 2015), possesses a great diversity of wetlands that serve as habitat to a large variety of species either permanently or temporarily, being bogs the most common in the province (85%; Pellerin and Moulin, 2013). As other Canadian provinces, Quebec has been undergoing a notable urban and consumption transformation (Asselin, 2011; Simmons and Bourne, 2013). Provincial statistics indicate continuous population growth (Institut de la statistique du Québec, 2014), which may be accompanied with expansion of infrastructure and public services at the cost of wetlands loss. In the region of Montreal, around 85% of wetlands were destroyed by 2015 and devastation may continue (Gerbet, 2015). In the Eastern Townships, where 2.1% of the territory is occupied by wetlands that host a rich fauna (e.g., Palm Warbler, Rusty Blackbird, Goldeneye, Yellow Perch, Smallmouth bass, Walleye) the situation is not much different (Canards Illimités Canada, 2007a). Urban expansion, artificialization of riverbanks, water treatment stations and other man-made constructions are the main stressors in this region and other ones. Comprised between the regions of Mauricie, Lanaudière, Montérégie and Centre-du-Quebec, the lake Saint-Pierre, one of the richest biospheres in the world, shelter extensive wetlands and waterfowl that are critically disturbed by various sources (e.g., navigation practices, input of pollutants, water level manipulation; Canards Illimités Canada, 2007b; MDDELCC et al., 2013).

In the high-latitude coastal regions of Quebec, conditions are favourable for the formation of salty marshes and optimal nesting of coastal birds (e.g., herons, roseate tern, herring gull) (Barbour and Billings, 1988). Nevertheless, drastic climate changes at these northern locations are predicted to produce critical impact on ecosystems (Canards Illimités Canada, 2009). The spillage of hydrocarbon-based products from commercial navigation is another critical and constant threat to coastal habitats. To illustrate the gravity of this risk we can name the case of 2015, when 14 oil spills occurred in the north of Quebec (MDDECC, 2016). Moreover, large hydroelectric projects have also influenced a number of wetlands at these locations (e.g., Outardes and Manicouagan rivers; Canards Illimités Canada, 2009). One specific example of this situation is the bogs notably perturbed by La Grande River installation, which requires important deviations of the natural river to supply 97% of the energy employed in Quebec (MERN, 2012).

Table 1
Data and corresponding sources employed.

	Data	Source data type	Transferred data type
1	Wetland inventory	Shapefile	WMS
2	Wildlife	Shapefile	Geojson
3	Provinces of Canada	Shapefile	Geojson
4	Regions of Quebec	Shapefile	Geojson
5	MRC of Quebec	Shapefile	Geojson
6	Fire	KMZ	Geojson
7	Invasive species (Hemlock looper)	Shapefile	Geojson
8	Power lines	Shapefile	Geojson
9	Highways	Shapefile	Geojson
10	Population	CSV	Json
11	Pollution sources	CSV	Geojson
12	Drought	Shapefile	Geojson
13	Water quality	Kmz	Geojson
14	Water quantity	Kmz	Geojson
15	BaseMap1	Raster	WMS
16	BaseMap2	Raster	WMS

Governmental and non-governmental institutions make continuous efforts to protect and conserve these valuable lands and biota by exploiting new technologies but also considering legal aspects to achieve conservation purposes (e.g., LégisQuébec, 2016). Many territories have already implemented urban plans that include regulations for preservation of these and other natural areas (e.g., Longueuil Direction de l'aménagement et de l'urbanisme, 2014; Ville de Gatineau, 2016).

3. Data selection and formats

Table 1 summarizes the available data used in this project. Wetlands polygons are one of the main geospatial components of the map. Five main types of wetlands (bog, marsh, swamp, shallow water, non-classified), derived from satellite imagery and photography are included (Ducks Unlimited Canada, 2016d). Specific wetland biodiversity data was not available; however, we include a fauna habitat layer to facilitate the identification of species within wetlands polygons. This dataset was established from wildlife inventories and other thematic information (MFFP, 2016a).

Because decisions about conservation, territorial and land use planning are taken at various political divisions (Fig. 1), three main levels of administrative divisions were integrated in a multiscale database (Section 4.2). Efficient preservation of natural habitats also requires identification of stressors in order to develop or improve management strategies. Many representative stressors were recognized to affect wetlands and biodiversity in Quebec (Fig. 1). Below we present the stressors that are part of the geoportal. They were chosen on the basis of their availability and pertinence to the project.

In Quebec metropolitan areas, two of the main pressures on these ecosystems are the notable urbanization and industrialisation (e.g., Queste, 2011). Information about population related to these processes at regional and MRC (Municipalité régionale de comté) levels are considered for analysis (St-Amour et al., 2015). Manufacturing, production and processing sites produce detrimental substances that can affect quality and quantity of water, air and soil. Mining activities, for example, uses large volumes of water for petroleum, minerals and gas exploitation (Ptacek et al., 2013), endangering availability of this essential resource and possibly altering hydraulic functions of wetlands. A layer containing multiple pollution sources (e.g., Chemical, Paper, Oil industries, Power Plants and others), as well as water quantity and quality data produced by the Open Government Program are incorporated in the geoportal. Highways and roads can transport sediments, chemicals and other polluting elements coming from industry, agriculture and urban areas into these ecosystems. Moreover, because noise pollution from road traffic can also influence birds' behaviour (Parris and Schneider, 2008), they are significant stressors of wetlands

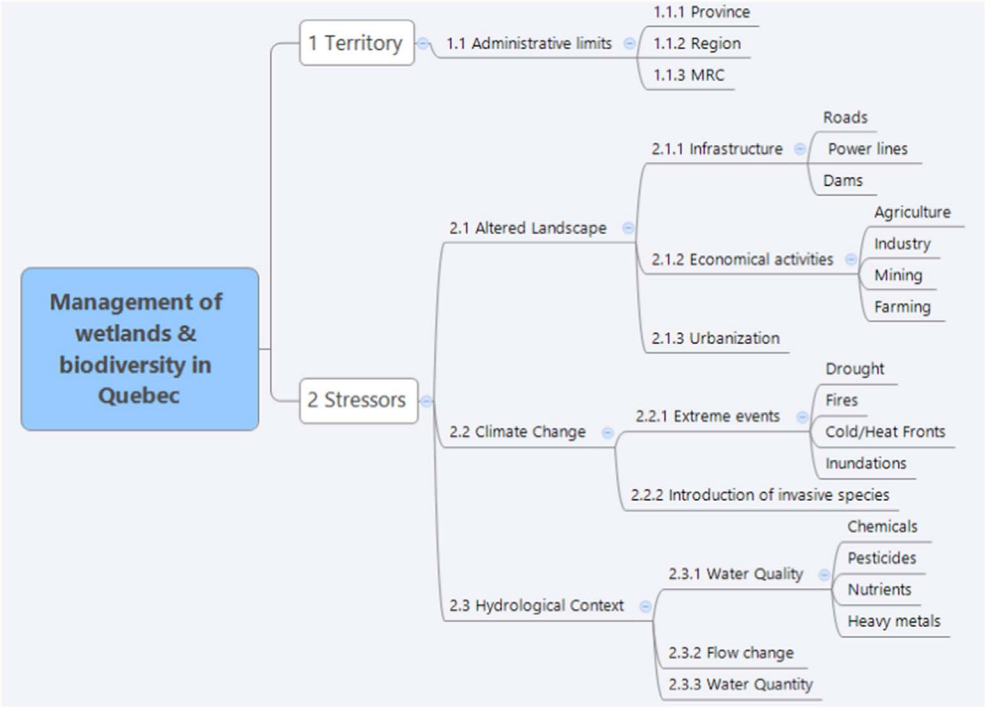

Fig. 1. Summarization of aspects taken into account in the conservation of wetlands and biodiversity. Managing territory and stressors are required to preserve natural habitats.

biodiversity to be taken into account. Another agent notably affecting wetlands is the generation of hydropower (Rochefort et al., 2011). Because Quebec is the largest producer of this renewable energy in Canada (NRCAN, 2016b), installation of transmission lines is also an important factor to be considered in the development of a balance approach for conservation of natural habitats. Already 2.9% of wetlands of the Saint Lawrence River basin are influenced by hydraulic transportation lines (Governement du Québec, 2016) and a number of ecosystems located in the rivers La Grande, Eastman, Sainte-Marguerite, Toulnustuc and Romaine undergo a similar situation (Rochefort et al., 2011).

Anthropogenic activities have a negative impact on these and other natural systems, nevertheless, other factors must also be taken into account. Climate change produces important variations in precipitations, temperatures and other variables that can modify patterns of drought, fires and floods (e.g., Anderson and Bausch, 2006), altering directly or indirectly ecosystems (e.g., Erwin, 2009; Wrona et al., 2006). Drought and fires principally impact the prairies of Western Canada (e.g., Michaelian, 2015; NRCAN, 2016c); however, registers indicate that these events have also significantly influenced some areas in Quebec (National Forestry Database, 2016; SOPFEU, 2016). The current implementation considers fire data and a spatio-temporal drought layer for the year 2014.

Presence of invasive species in Quebec wetlands is also a serious problem to biodiversity (Martin, 2014). Critical cases were found in Abitibi-Témiscamingue (CRRNT, 2013), along the Saint Lawrence river (Savage and Jean, 2008) and in other areas (Bédard et al., 2008). Levels of defoliation and spread of the hemlock looper, one of the most harmful alien species in Quebec (NRCAN, 2015), are also available. Most of these data were produced from the combination of satellite imagery and aerial surveys (MFFP, 2016a).

Regarding the data formats, various sources and transferred types were employed (Table 1). The widely used Web Map Service (WMS) and the Web Feature Service (WFS) supply simple Hypertext Transfer Protocol (HTTP) services for requesting geo-referenced map images and geographical features used in the geoportal (OGC, 2006). Many of the geospatial data vectors provided are represented as shapefiles, although they are available in other popular encoding formats such as Keyhole Markup (KML) and the Geography Markup Language (GML). The geographic JavaScript Object Notation (GeoJSON), which encodes a variety of geographic elements, has been broadly employed for data transferred because of its flexible capabilities for integration and interoperation of various service-oriented resources (OGC, 2015).

4. Methods

4.1. Overview of the system architecture

The evolution of technology has dramatically changed the way data and information are acquired and diffused. Advanced and powerful data storage constitutes the framework that makes possible Web mapping. Commercial and open-source tools (Table 2) are at hand to build spatial data infrastructures. Potential libraries for creating and customizing interactive maps are continuously under development (e.g., Leaflet, Open Layers, Kartograph, CartoCSS and others).

The system architecture of our prototype is based on the client-

Table 2
Examples of Commercial and open-source tools for Web mapping.

	Commercial	Open-source
Mapping engine	ArcGIS for Server Envinsa Oracle MapViewer ArcIMS Autodesk's Infrastructure Map Server MiraMon	MapServer Mapguide Open Source Deegree MapZoom Mapnik TileStache Geoserver
SQL database	GeoMedia WebMap Oracle ESRI Spatial Database Engine Microsoft SQL CartoDB	MySQL PostgresSQL CartoDB (research and Education) MangoDB SQLite
Web application frameworks and libraries	DHTMLX ExtJS Smart GWT	AngularJS Grails-Groovy (Geo)Django Leaflet

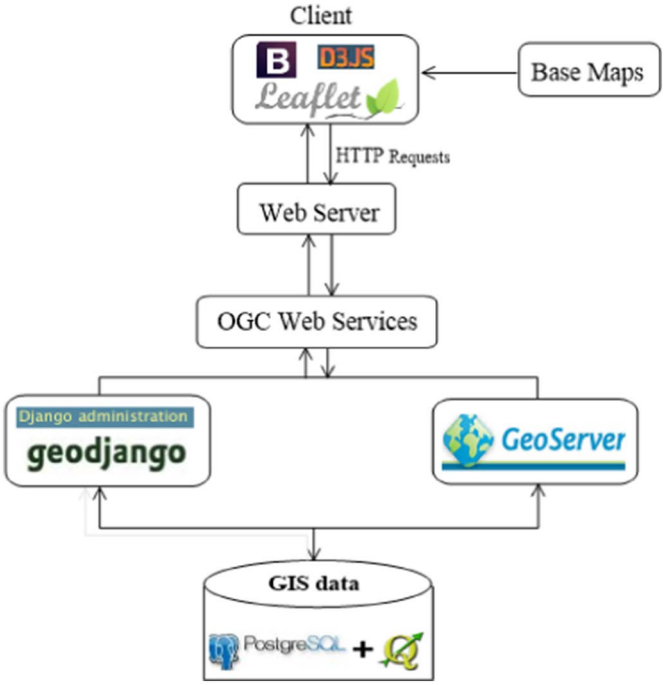

Fig. 2. Simplified system architecture.

server model (Fig. 2), where the first side (Client) performs requests that are processed by the second part (server) to provide suitable responses. The server side was developed by exploiting the Django REST framework, more specifically the GeoDjango extension, while Bootstrap, Dj3 and Leaflet were used to set up the presentation and Web-GIS interfaces, respectively. One advantage of Django is that it allows performing queries by using simple Python codes rather than repetitive SQL statements (Holovaty et al., 2009). Besides, recorded data can be easily managed through the Django administration interface. This high-level python geographic web framework support object-relational procedures on datasets that can be stored in various databases such PostgresSQL, MYSQL, Oracle and/or SQLite. In our case, most data were imported into a PostgreSQL spatial database. Shapefiles, csv and kmz data were first translated into Structured Query Language (SQL) format and then imported into the database. Models that will integrate the Django project were defined for each dataset. The open standard map server GeoServer (Deoliveira, 2008) is also considered as part of the system architecture. Particularly, wetland data were stored therein and WMS images were used for their mapping. The corresponding WMS layer style was defined in QGIS and exported as Styled Layer Descriptor (SLD) (OGC, 2002) to Geoserver. It must be highlighted that cross-origin needs to be authorized and connexion with the server first initialized to access and visualize Geoserver layers.

4.2. Database organization

The multi-relational database employed in this project was designed by using multiple heterogeneous datasets. Fig. 3 shows an extract of the database described in this section.

In order to perform multiscale queries a hierarchical structure for the administrative divisions of the Province of Quebec was considered (Fig. 3). Tables for each division were defined and relationships between them established based on keys. Administrative divisions could be extended to the rest of Canada. It will also be possible to replace administrative divisions in a province with natural divisions such as watershed boundaries. Each table has a primary key (PK) that is set up to automatically generate a unique number for each division row. Foreign keys are defined in the child tables (Region, MRC) to be uniquely related to the parent table (Province). A one-to-many relationship is also set up between each division table and the corresponding population table. On the other hand, because many types of fauna habitats and pollution sources can be found in many MRCs, but at the same time many MRCs can contain various fauna habitats and industrial sites, a many-to-many relationship is established between the corresponding tables. Similar analysis has been done to establish the relationship between the fire and the MRC tables.

Climate change-related data are also part of the database. Models for fire, drought and defoliation levels can be accessed via the Django Server. Moreover, creation, update and deletion of objects in a model are possible in the Django site.

5. Interactive geoportal

5.1. General structure and components

The main interface of the geoportal is shown in Fig. 4. Basic functions such as dynamic scale, zoom in/out, drawing and measuring are accessible via small icons on the left. On the bottom right, a mini-map to locate the area of interest is available. Layers and basemaps are organized in an expandable-collapsible panel located on the top right of the interface Fig. 4. Legend of certain layers comprising various categories (e.g., drought, wetlands, wildlife) are displayed in a separately panel when activated, while symbols for those containing one category are shown directly in the panel.

The structure of the prototype allows researchers to add their own analysis tools in the side panel. For this purpose, the user can define their functions in the Geodjango framework as a view. These new functions will receive the demands of the procedures specified in the Leaflet-based interface, execute the corresponding operations on the models and return the responses to be displayed (the reader is referred to *https://docs.djangoproject.com* for more detail description on function's set up in Geodjango). An evolution of the prototype is in progress in order to allow access to new tools. Main available functionalities are discussed below.

5.2. Main functionalities

The administrative multiscale function allows visualization and analysis of data at various spatial scales (Fig. 5). The query is performed by a number of request functions written in python and by exploiting the JQuery library; the communication mechanism is based on messages encoded in GeoJSON. When a particular region of analysis is selected, a request calls the corresponding view function, which after being executed by Django returns an HTTP response containing the target GeoJSON object. Population at different political levels can be estimated and compared via a bar graph which is accessible via popups.

The drought monitoring tool permits to map the temporal and spatial evolution of drought by using a jQuery responsive slider (Fig. 4). The process is carried out by invoking a series of request functions similarly to the multiscale filter. Moreover, a query tool to display different levels of defoliation (Low, Moderate, High) produced by the hemlock looper is available in the responsive sidebar. Similar to the drought layers, different colours were used to easily identify the defoliation intensity. Request of fires by location is also facilitated via application of a filter operation to the corresponding table. Another functionality implemented is the mark clustering, used to manage highly dense point data (manufacturing sites). Clusters change dynamically according to the zoom level (Fig. 6a, b), enabling a cleaner visualization and better interpretation of the spatial distribution of data (e.g., density of industry at different locations can be efficiently compared). A buffer functionality was also developed to support rapid identification of wildlife habitats put at risk by nearby manufacturing sites. Many studies reviewed the usage of buffers for protection of these and other natural environments (Castelle et al., 1994; Raymond et al.,

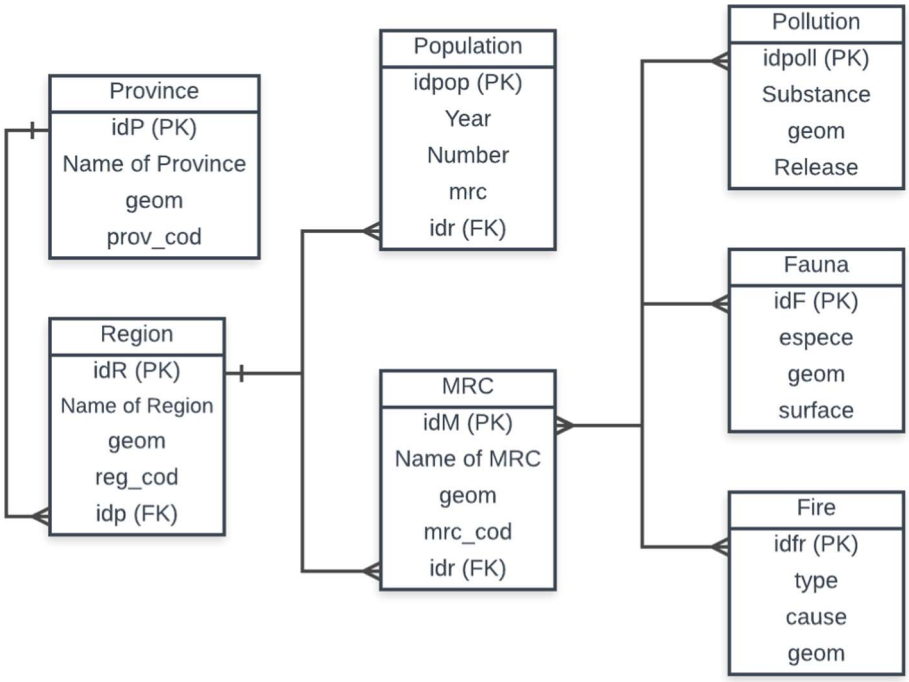

Fig. 3. Extract of the Database (PK: primary key, FK: secondary key).

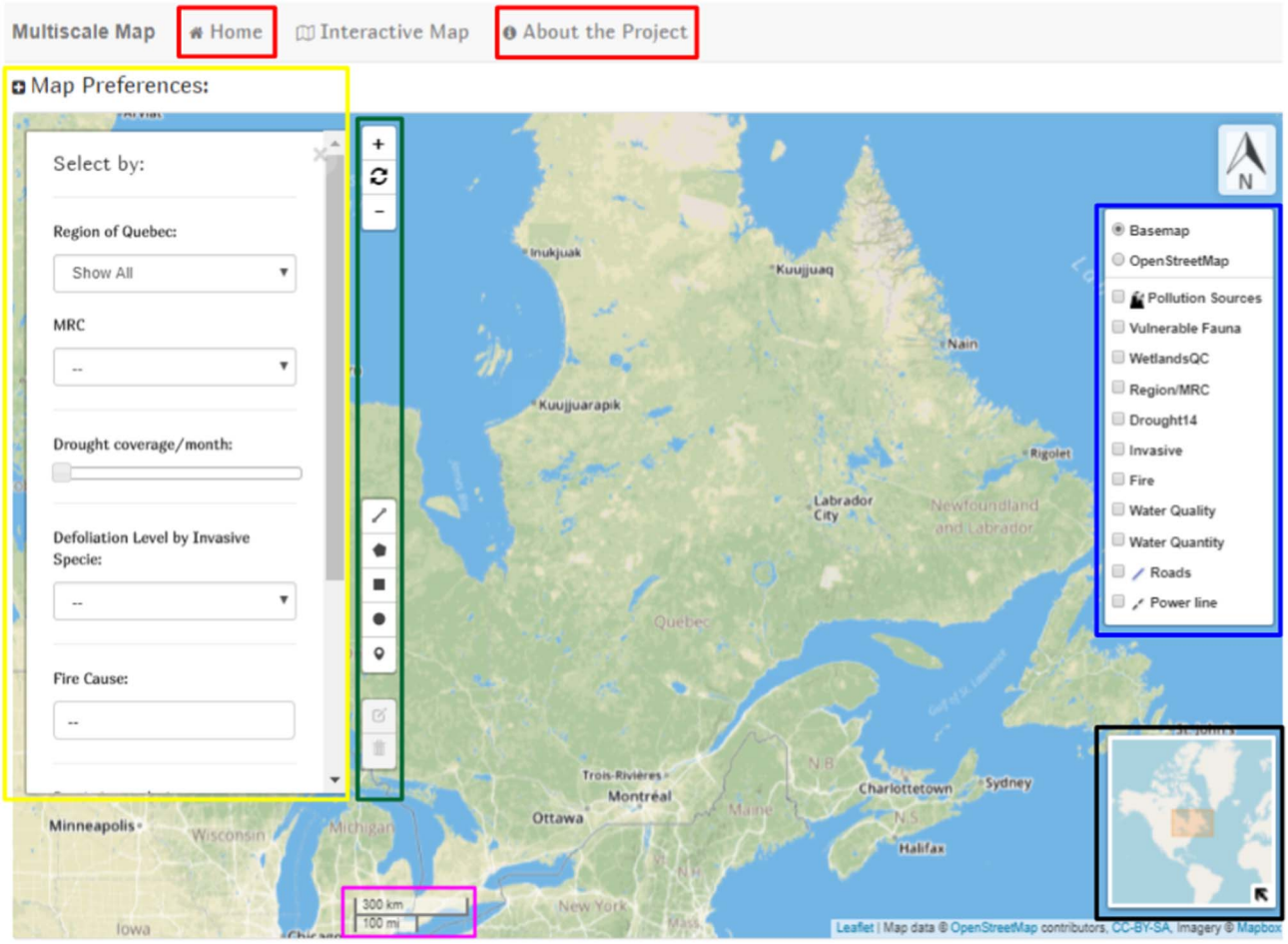

Fig. 4. Interface of the geoportal. Main components are highlighted by coloured rectangles (Red: indicate the *Home* and the *About the project* tabs. Blue: expandable-collapsible panel containing data. Black: Minimap. Green: zoom, drawing, measuring and reset viewed tools. Pink: dynamic scale. Yellow: Query tools contained in the Map Preferences responsive sidebar). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

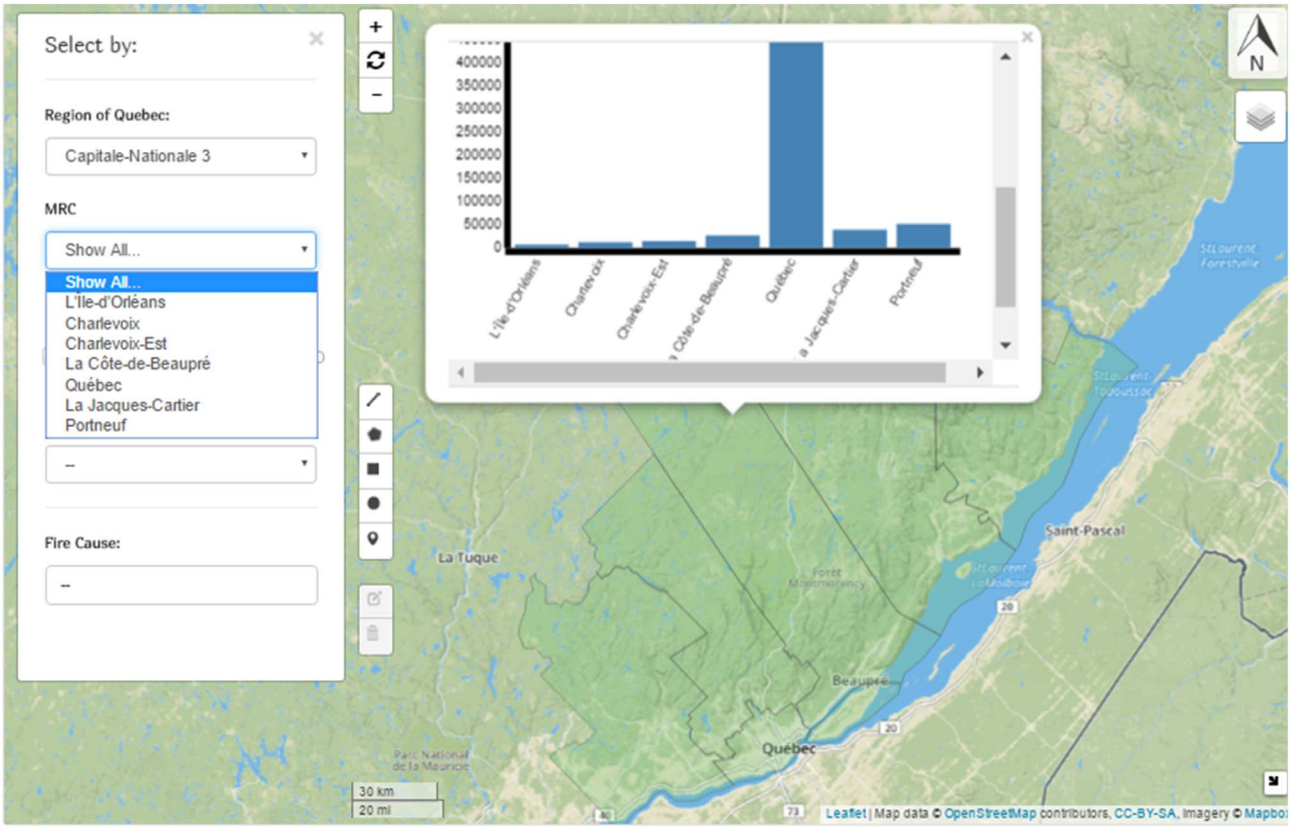

Fig. 5. Interactive Map showing an example of the multiscale functionality. The population distribution can be displayed by clicking on the region or MRC polygon.

2003; Smith and Chow-Fraser, 2010; Watts et al., 2009). Based on these studies and the available information about the type and total releases of contaminants for each individual pollution source, it is possible to perform a first evaluation of the impact on Quebec wetlands health. For example, McElfish et al. (2008) suggest an effective distance between 30 and 50 m for removal of nitrogen. By using the buffer tool we can identify if industrial sites realising this type of pollutant respect the suggested distances for protection of this wetland function.

An additional tool was implemented to identify another serious problem in Quebec: the fragmentation of ecosystems. This spatial functionality returns geometry (broken habitats) as the results of intersecting the geometry of roads and power lines with that of the natural habitats. This simple yet sound tool can aid the work of conservationist and local governments by providing a quick and general location of fragmented habitats in the entire province, as well as to examine where this situation occurs more often. Combination of custom SQL queries were used in the design of these geoprocessing tools.

6. Discussion

Accessibility to various data for management of ecosystems is experiencing a notable improvement. Our open cartographic platform allows communication and integration of multiple comprehensive spatial and temporal datasets. In this section we discuss the usefulness

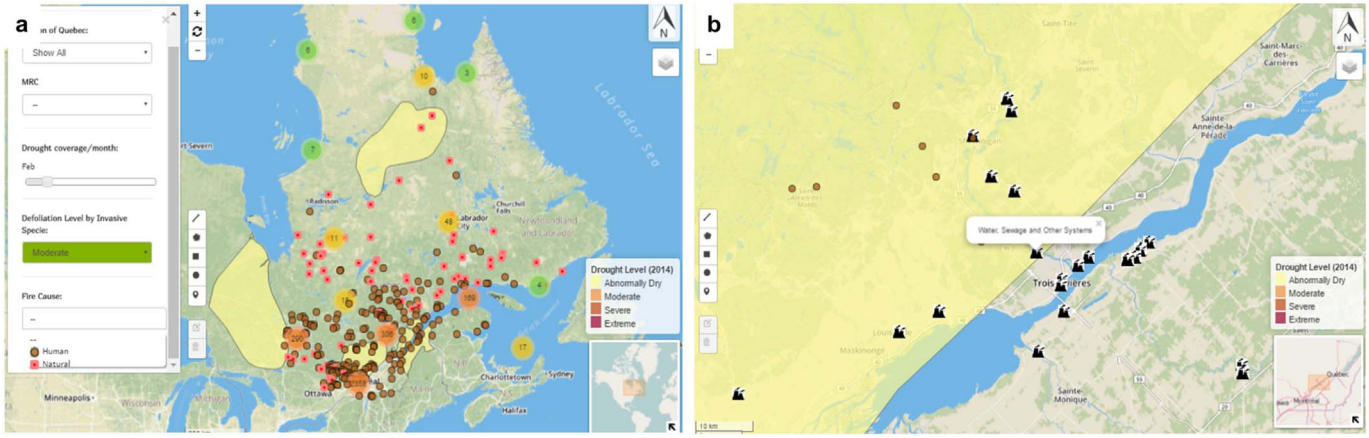

Fig. 6. a) Examples of results provided by the defoliation level query and clustering functionalities. Abnormally dry levels affected various areas of Quebec in February 2014. Different colours of clusters indicate different concentrations of manufacturing sites across Quebec (orange: large, yellow: medium, green: low). Location of human caused (brown dots) and wildlife fires (red squares) are represented as well. b) Result of zooming on a specific region in a). Description of a particular type of manufacturing site is displayed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

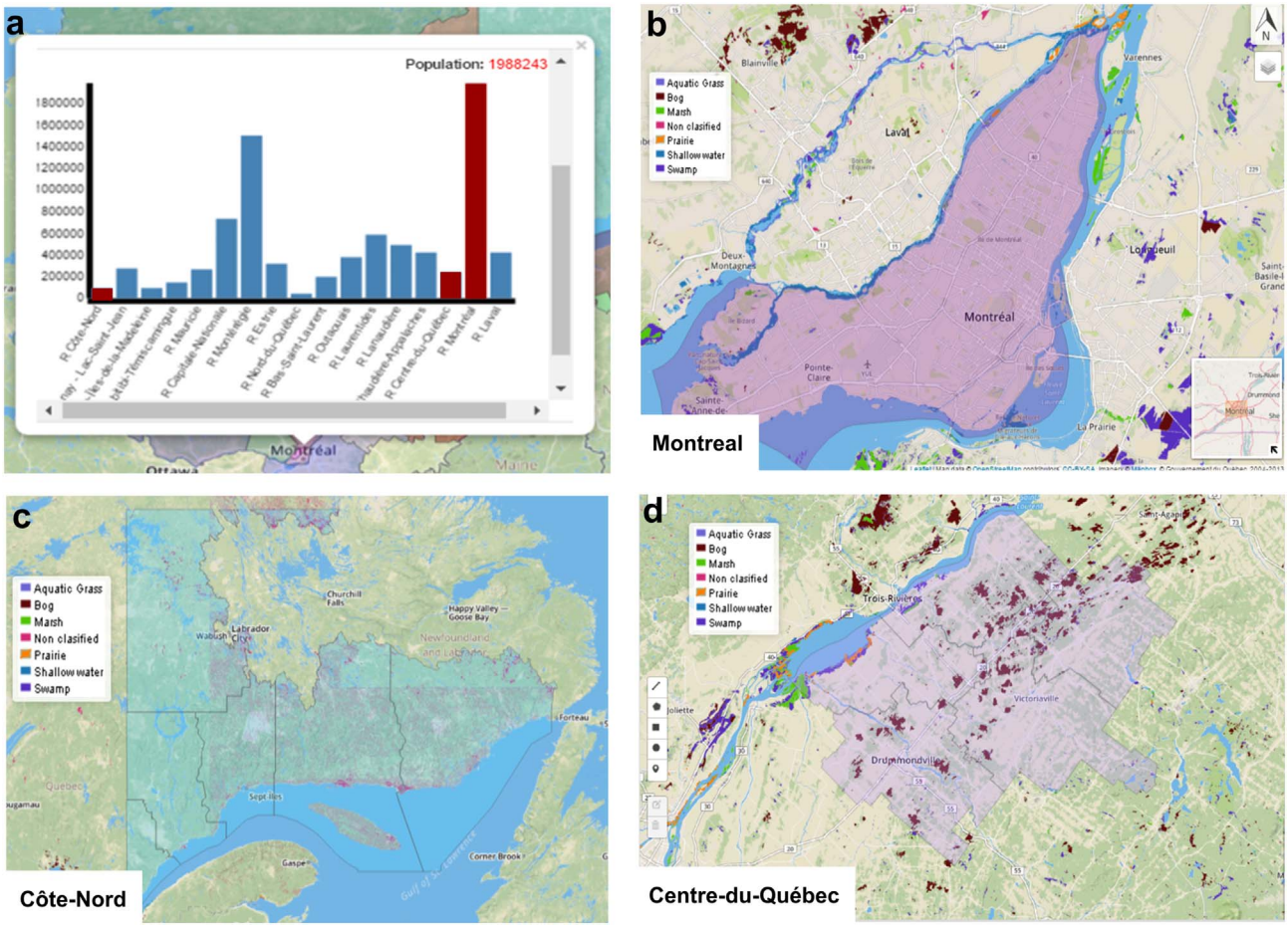

Fig. 7. a) Bar graph showing the population distribution at regional level for the year 2014 in the province of Quebec. The red rectangle indicates the population for three regions (Montreal: 1,988,243 persons, Côte-Nord: 94,906 persons; Centre-du-Quebec: 239,000 persons) represented in panels (b–d). (b–d): cartographic visualization of wetlands in Montreal (b), Côte-Nord (c) and Centre-du Quebec (d). A reduced number of wetlands are observed in Montreal in comparison to regions in c) and d).

of the system to different types of users. Furthermore, future developments that will support a better understanding of the risks to Quebec ecosystems and the implementation of appropriate conservation policies will be explored.

6.1. Case examples by user type

6.1.1. Land and ecosystem planners

Decisions about the territory are taken at different political levels. A general visual overview of wetlands and population distribution can provide a first hint of demographic pressure on these natural lands. Efficient studies can be performed on individual regions and municipalities thanks to dynamic multiscale queries. Human population distribution can be effectively compared via bar graphs (Fig. 7a), being possible to evaluate the relationship between this variable, the density of wetlands and dependent species at different administrative scales (Fig. 7b–d). The effects of the stressors proposed (either natural or human), as well as the possible responses of wetlands can be studied on those different scales. This information may contribute to the development of planning strategies for resettlement areas to reduce conflict between conservation of ecosystems and urban and economic expansion.

6.1.2. Infrastructure managers

One of the first stressors considered in this work were infrastructure elements linked to urban development, such as roads and highways (main mode of transportation in Canada; Transport Canada, 2011). Similarly, important power lines have been installed to respond to the important local and international demands of electricity (MRNF, 2013). However, construction and maintenance of these facilities have been accompanied with negative direct and indirect consequences on wetlands and biodiversity (e.g., introduction of exotic species) (MFFP, 2016b, Bédard et al., 2008). The James Bay project, consisting of a series of hydropower stations, represents a clear example of loss of habitat for birds in Quebec (Cheskey et al., 2011). Through the Web map we can appreciate other areas where these elements may have critical influenced on ecosystems such as in southern Quebec, where a high density of roads and power lines, is observed (Fig. 8a). Recently, Tougas-Tellier et al. (2015) estimate that, although current presence of these invasive species in the Saint Lawrence River is not critical, potential spread is expected due to modified climate conditions and water level drops. Although, the current application allows to identify areas affected by one type of invasive species (hemlock looper), the database is planned to be populated with more alien data. This information will be useful to infrastructure developers by helping them to understand the interaction between roads, power lines and presence of exotic species in adjacent natural habitats to optimize sustainable projects. Another major problem linked to the construction of these linear structures is the fragmentation of natural habitats. The prototype proposed provide rapid outputs that can aid decision-making of infrastructure to prevent further habitat loss and quality detriment in Quebec. For example, a first manual inspection of the map indicates that a notable number of complexes of wetlands and fauna areas are divided by roads and electric lines, particularly in the Saint-Lawrence corridor. More precisely, by applying the fragmentation tool, we determine that 3% and 22% of the wildlife habitat in the entire province

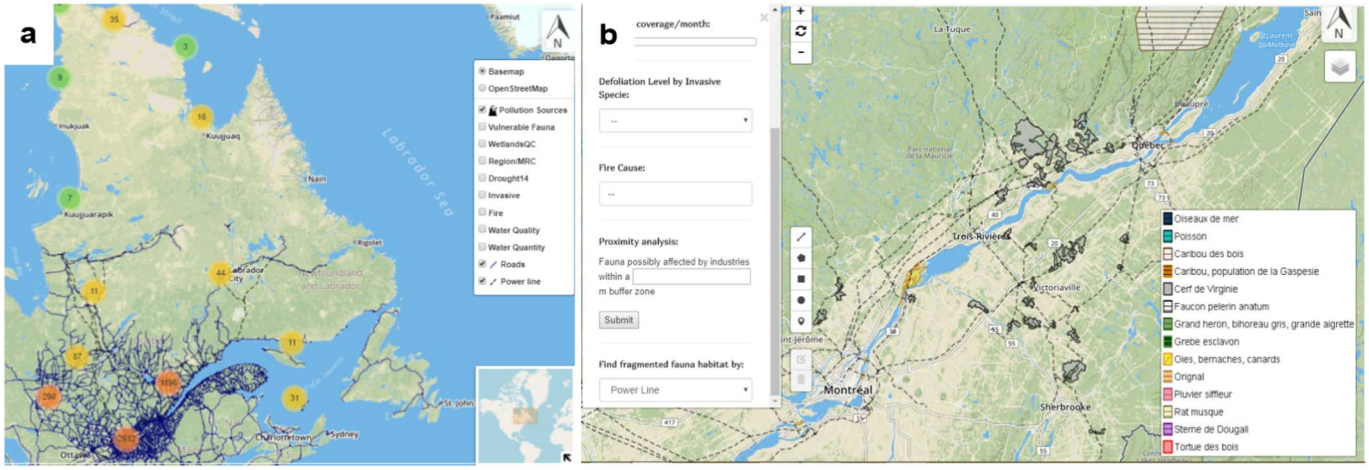

Fig. 8. a) Roads, power lines and manufacturing sites across Quebec Province. (b) Results from the application of the fragmentation tool. An example of fauna habitats fragmented by power lines is displayed: white-tailed deer (grey), ducks (yellow), caribou (white with brown line pattern). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

has been broken by power lines and roads, respectively (Fig. 8b). Although, relocation of existing roads and power lines may be difficult, identification of fragmented habitats and analysis of metapopulations could improve resilience to other changes and mitigate further ecological impacts on remaining intact ecosystems, as well as, provide guidance for future engineering projects (e.g., Governement du Québec, 2014). While the current prototype does not enable the latter study, a further implementation that will contribute to that purpose is planned to be included in future work.

6.1.3. Conservationist groups

Assessment of how certain activities influence natural environments remains a critical issue in the Province of Quebec. The analysis of distribution and proximity of manufacturing sites to ecosystems can be very useful to evaluate how human activities threaten them. Using the portal industries, such as paper, wood, food as well as water treatment plants were identified close to wetlands (Fig. 9). Pathogens conveyed by road runoff waters from these sites may critically impact the local biota. In this context, the buffer functionality can help conservationist groups to efficiently verify if existing protection zones are respected and to redesign them, where necessary, to achieve the conservation objectives. For example, in order to preserve waterbirds from disturbances generated by nearby industrial operations the Government of Canada (2016b) suggests a mean distance of 150 m between the installations and the colonies. However, results obtained from the buffer tool indicate that a significant number of manufacturing sites are located at shorter distances from wildlife than recommended (Fig. 9a). Fig. 9b displays an example of waterfowl and white-tailed deer habitat possibly threatened by pollutants in the region of Montérégie. The portal enables users to observe the notable emissions of ammonia (~173 t) and particular matter (~68 t) from nearby manufacturing sites. Equally, mining and petroleum industries at distances lower than 30 m of seabirds and deer populations have been detected in the region of Gaspésie (Fig. 9c). Contaminants and noise generated by these operations could negatively modify avian behavioural reactions in this region (Ortega, 2012). Besides these stressors, the presence of invasive species (Fig. 9c), possibly introduced by anthropogenic activities, can compound the health of the regional wetlands and native species (Genovesi and Shine, 2003). Likewise, by using the fragmentation tool conservationists can rapidly identify degraded wetlands by fragmentation and determine which sectors of municipalities or regions require development of environmental guidelines or monitoring.

6.1.4. Natural resource managers

A notable percentage (10%; MFFP, 2014) of the Quebec economy is based on exploitation of natural resources for multiple purposes. The clustering visualization instrument shows the distribution and density of industries, possibly providing to natural resource managers a first glance of the level of stress and strain on ecosystems at different locations. By exploiting this tool a higher density of manufacturing sites in southern province was identified (Fig. 10), where also a high concentration of roads and power lines is found. The notable lesser concentration to the north may be explained by the extreme and challenging climate conditions that make difficult the development of certain economic activities (Pierre, 2015). Moreover, with the aid of the drought coverage tool, it is possible to visualize links between industry agglomeration and water availability. For example, the areas affected by moderate drought on December 2014 coincide with the location of high density of industrial sites (Fig. 10a) and population (Fig. 7a) in the region of Montreal. The frequent occurrence of drought in this area (Fig. 10a, b), may probably indicate notable loss of wetlands or that the hydrological functions of remaining wetlands are deteriorated. This interpretation indicates that an evaluation of relocation of some industries may be required. Similar information can be inferred from the system that could support decision-making of natural resources managers and stakeholders to ensure a more sustainable interaction between the industrial activities, natural resources and landscapes.

6.1.5. Emergency managers

Existing studies (e.g., Erwin, 2009; Tougas-Tellier et al., 2015; Vallières, 2013) indicate that climate change may increase recurrence of extreme events possibly changing biological processes and compounding invasion of exotic species. Under this situation, there is an increasing need for efficient and cost-effective emergency programs. In this perspective, the proposed Web-GIS can notably contribute to these programs by providing updated information about areas affected by extreme events and alien species that need to be monitored by the managers, such as areas in northern Quebec, affected by abnormally dry levels and wildfires (Fig. 10b). Our database can be easily edited, allowing incorporation of new events that can disturb these lands and dependent species. For example, updated fire geospatial data is possible to be introduced by year and type, being their location helpful to infer possible repercussions on wetlands. This may be important considering the notable number of fires events that have recently taken place in Quebec (SOPFEU, 2016) and other Canadian provinces (e.g., Alberta; NRCAN, 2016d).

By using the prototype, managers can identify invasion of hemlock

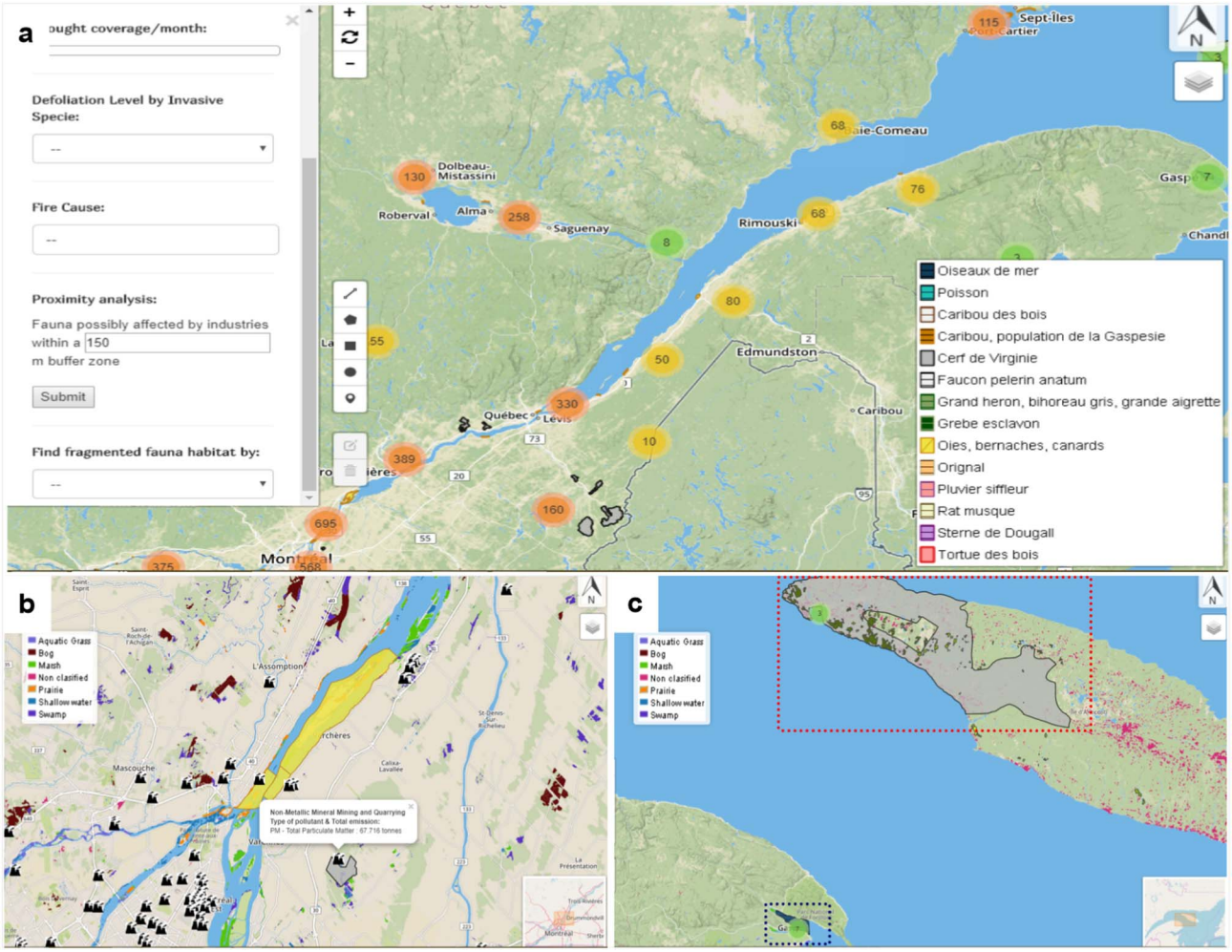

Fig. 9. a) Fauna habitats possibly affected by industrial operations within a 150 m buffer zone b) Zoom on wildlife habitats, mainly white-tailed deer (grey) and ducks (yellow), corresponding to the region of Monteregie c) Example of pollution sources (as clusters) close to white-tailed deer areas (grey) in the Anticosti Island (dashed red rectangle) and seabirds (dark blue) in north-eastern part of the Gaspesian coast (dashed blue rectangle). Different intensity of green indicates the level of defoliation by the hermlock looper (dark green: severe, bright green: medium, lime: low). Habitats of wildlife threatened by industries coincide with the location of wetlands in b) and c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

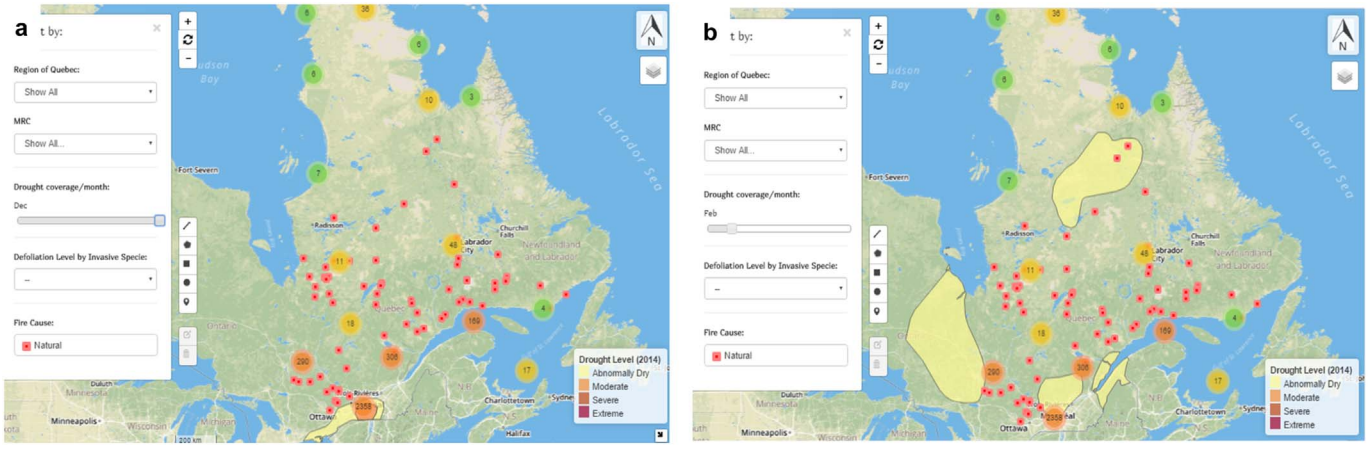

Fig. 10. Distribution of manufacturing sites as clusters, natural fires (red squares) and drought level for (a) December and (b) February 2014. Abnormal and moderate levels of drought are found in southern Quebec, where more than 2000 manufacturing sites are located. Some natural fires occurred in abnormally dry areas in the North of Quebec (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

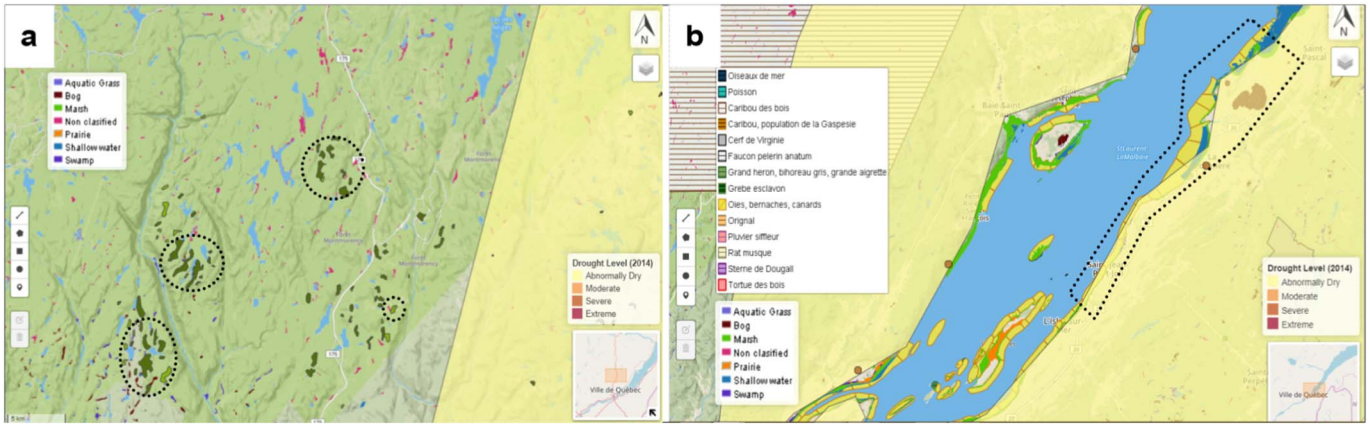

Fig. 11. a) Zoom on wetlands in the National Park of Jacques Cartier (Capitale-Nationale) affected by the hemlock looper (highlighted by the dashed black circles) and near areas affected by drought in January 2014. High (dark green) and moderate (bright green) intensity of defoliation are identified. b) Wetlands and fauna of the Saint Lawrence corridor impacted by abnormal dry levels (January 2014). The dashed black polygon illustrates one example of this situation: duck habitat (dark yellow), shallow water (blue), marsh (green), bog (brown) are overlapped by the abnormally dry area (light yellow). Human-caused fires (brown dots) are also observed. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

looper, producing notable levels of defoliation, in some peat bogs and shallow water wetlands of southern Quebec (Fig. 11a). The drought coverage tool can also be used to visualize abnormally dry regions in January 2014 close to those wetlands (~20 km far away; Fig. 11a) and along the Saint Lawrence corridor (Fig. 11b), where also a number of human produced fires are noticed. It must be emphasized that natural fires in the province have already been linked to the occurrence of drought events (MFFP, 2016c) and episodes of alien species (MFFP, 2015). These examples illustrate how emergency managers could use the system's functionalities not only to visualize individual types of events but also integrate them in a common interface, facilitating the interpretation of possible correlated risks.

6.1.6. *Housing developers*

Companies interested on developing housing districts may decide where to place the constructions depending on the information provided by the system. For example, from the buffering tool environmentally sensitive habitats can be identified and avoided during the planning process.

6.2. *Perspectives*

The combined effects of agents such as highways, power lines, invasive species, urban, agriculture and industrial sprawl can seriously modify the composition of ecosystems. Developing tools for monitoring continuously their state is required due to their environmental, economic and social importance.

The current geospatial application already enables interpretations that can support a better and more sustainable urban planning for protection of wetlands and native species, however, further analysis can be achieved by incorporation of novel functionalities. Inclusion of population levels and wetlands distribution through time may yield to a more comprehensive analysis of these variables and their spatio-temporal correlation. Likewise, evaluation of the temporal evolution of degradation due to fragmentation of natural habitats can be critical to improve conservation and restoring programs at various scales. Acquisition of complementary data (e.g., traffic density, voltage intensity, specie population) can be used to design indicators that could help to evaluate the interconnections in wetlands complexes and improve the understanding of dynamics of flora and fauna among patches.

Envisioning a future metapopulation study, a geoproccesing tool for analysis of patches proximity, density and size is planned to be implemented. Moreover, in order to enable a more direct assessment of the anthropogenic pressure on wetlands and support decision making by various agencies, an ecological integrity index based on metapopulation indicators is under development (Charland, 2017). This function will indicate where anthropogenic pressures are more notable, suggesting government environmental agencies where to concentrate their efforts to protect natural habitats at high risk. Conservationists could also benefit from a patch-proximity functionality to rapidly identify isolated wetlands and develop strategies to prevent their disappearance. We intend, in future works, to setup a Web Processing Service (WPS) interface to enable these procedures.

7. Conclusion

We present a friendly and dynamic web mapping implementation that provides useful services to assist in the decision-making process to effectively manage, and even restore wetlands and biodiversity in Quebec. This Web-based GIS supports preliminary evaluation of environmental health of wetlands and wildlife in the Province of Quebec. Although the study was limited to one province, it can be easily extended to the national scale.

Among other benefits, the prototype offers the possibility of including new functionalities at relatively low cost because of its free and open-source nature. Exploitation of particular data (e.g., certain invasive species, environmental indicators) is still a challenge due to their restrained access or cost.

Wetlands are important not only for their ecological but also their social and economic effects. Their deterioration can yield to critical consequences such as increasing costs for water quality treatment, improved infrastructure for regulation of floods and programs for elimination of invasive species. Raising awareness of this situation at all sectors of society is essential for their conservation. In this context, interactive tools such as the one proposed can contribute to educational programs aimed to protect these and other natural habitats.

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